International Journal of Applied Aviation Studies, 5, Number 1

The Effect of GPS and Moving Map Displays on Navigational Awareness While Flying Under VFR

Stephen M. Casner

National Aeronautics and Space Administration
Ames Research Center
Mail Stop 262-4
Moffett Field, CA 94035-1000
U.S.A.

Abstract

Sixteen pilots rated their navigational awareness to be significantly higher when navigating using a GPS and moving map display than when navigating using pilotage. The same sixteen pilots then were asked to fly, as accurately as possible, over a circuit consisting of six checkpoints in an unfamiliar area. Eight pilots navigated between the checkpoints using pilotage (i.e., a sectional chart). The remaining eight pilots were given the same sectional chart and a GPS receiver featuring a color moving map display. Navigational accuracy was recorded at each checkpoint for all sixteen pilots. The GPS/Moving Map group navigated more accurately than the Pilotage group, although both groups performed within standards. Upon completion of the circuit, pilots were asked to fly the same circuit again, only this time without any navigational resources. Navigational accuracy was again recorded for each checkpoint. The GPS/Moving Map group performed significantly worse than the Pilotage group when navigation resources were taken away. Two pilots using GPS and the moving map were unable to find their way to the starting point of the circuit. Other GPS pilots made large errors in navigating to individual checkpoints. When asked to reassess their own estimations of navigational awareness during the second circuit, the Pilotage group raised their estimates while the GPS group significantly lowered them. These findings call into question unqualified beliefs and claims that advanced avionics systems enhance pilots' navigational awareness, and point to a need to teach pilots about the potential human factors pitfalls associated with advanced avionics systems.

Requests for reprints should be sent to Kay Chisholm, FAA Academy, AMA-530, P.O. Box 25082, Oklahoma City, OK 73125. E-mail to kay.chisholm@faa.gov.

Introduction

GPS receivers with moving map displays are often claimed to increase pilots' navigational awareness (Avidyne, 2005; Garmin, 2003). These claims are partly justified by some obvious advantages offered by GPS and moving maps. One only need consider the problem of locating the nearest suitable airport in the event of an emergency. GPS receivers pinpoint the position of the aircraft while moving maps instantly present the answer to the dire question of where to go. Many systems can also display the available runways, runway lengths, field elevation, and communications frequencies. In the case of an emergency, it is hard to imagine a more timely and useful information resource.

With examples such as this in mind, it is tempting to think of GPS and moving maps as having a supplemental effect on pilot awareness: further empowering already-aware pilots with more detailed information about their surroundings. However, the research literature tends to contradict this belief. Empirical studies have demonstrated a cost associated with not having to actively perform mental calculations and discriminations that are made automatically by a computer. Memory and awareness of information that is passively monitored has been shown to be significantly poorer than information that human operators generate themselves using mental problem solving and rehearsal (Slamecka & Graf, 1978; Glenberg, Smith, & Green, 1977; Craik & Lockhart, 1972). Observational studies of humans working with automation, in the aviation domain as well as others, have demonstrated poorer awareness among human operators who perform tasks with the assistance of automated systems (Uhlarik & Comerford, 2002; Savage, 1999; Billings, 1997; Endsley, 1996; Endsley & Kiris, 1995; Parasuraman, 1987). These studies draw a common conclusion: in an effort to make the human operator more aware by providing more information through automation, we sometimes make the human less aware. Wiener (1989) refered to this phenomenon as the *paradox of automation*.

This study attempts to answer two simple questions about the navigational awareness of pilots while flying under visual flight rules (VFR):

1. Do pilots believe they are more navigationally aware when flying with GPS and moving maps?
2. Does pilots' navigational performance agree with or contradict these beliefs?

Comparative verbal estimates of navigational awareness were collected from pilots as a measure of what they believe about GPS, moving map displays, and navigational awareness.

A simple comparative technique was used to determine whether or not pilots' performance matched their beliefs about navigational awareness. Two groups of pilots were asked to fly a circuit of checkpoints on a cross-country flight through an unfamiliar area. One group of pilots used pilotage (i.e., a paper sectional chart and visual references) to find their way to each checkpoint. The other group of pilots had the same sectional chart and visual references, but also used a GPS and moving map display. Navigational accuracy was recorded at each checkpoint. Upon completion of the circuit of checkpoints, all pilots were asked (unexpectedly) to fly the circuit again, this time, without the use of any navigational resources. That is, the pilots were asked to fly the circuit using only whatever familiarity with the area they had acquired during the first time around the circuit. Navigational accuracy was again recorded and compared.

Previous research suggested a simple hypothesis. Pilots using pilotage actively perform the navigational task. When asked to fly through the circuit of checkpoints a second time with no navigation resources, these pilots should enjoy a more detailed awareness of the area acquired during their first pass through the circuit. Pilots using GPS and a moving map display, on the other hand, serve as passive monitors while computers automatically perform the navigational task for them. When these pilots are asked to fly over the same circuit of checkpoints again, they should experience more difficulty because they maintain a lesser awareness.

Method

Participants

Sixteen pilots who met the following three criteria were selected on a first-come-first-served basis at a local airport. All pilots were legally qualified to act as pilot in command in the experiment airplane. All pilots had basic familiarity with GPS receivers and moving maps. All pilots reported that they did not have significant familiarity or experience with the area in which the data were to be collected.

Apparatus

The experiment airplane was a Diamond DA40 (Diamond Star) equipped with a panel-mounted GPS receiver and a color moving map display. All pilots were furnished with a current San Francisco sectional aeronautical chart that covered the area through which the experimental flight was conducted. The experimenter had access to an additional GPS receiver that was hidden from pilots' view.

Procedure

The sixteen pilots were told that they had to complete a cross-country flight that consisted of a series of nine checkpoints. It was explained that the first three checkpoints were intended as practice checkpoints as pilots made their way out to a circuit of six additional checkpoints, located in an unfamiliar area, that were of interest to the experimenter. The last six checkpoints formed a circuit as shown in Figure 1. The most distant checkpoint was approximately 105 nautical miles from the origin airport.

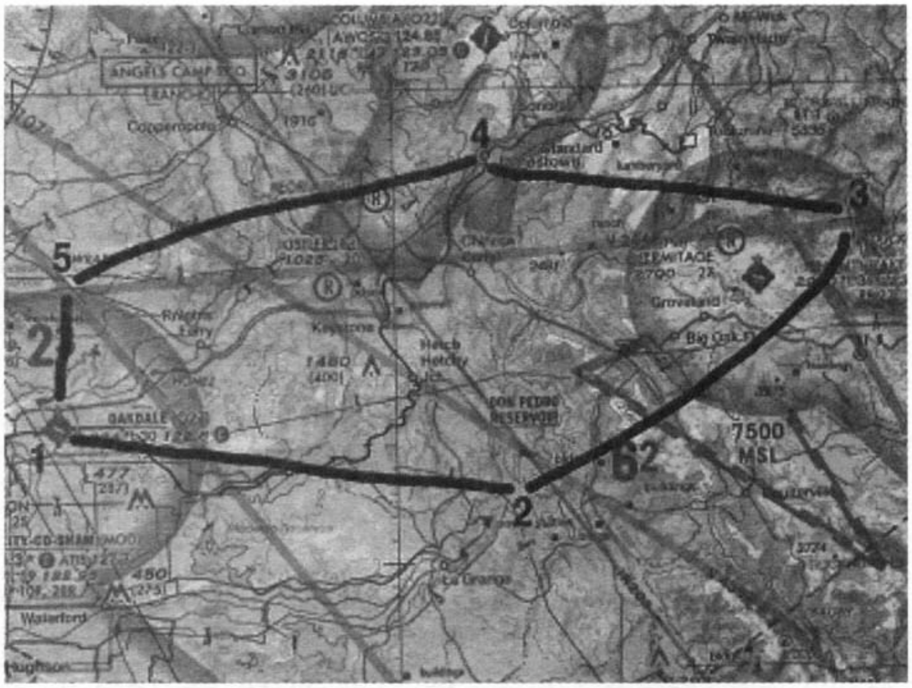

Figure 1. Sectional chart showing circuit of checkpoints.

Pilots had to find their way to Oakdale Airport, then fly over a series of four other checkpoints, and end up back at Oakdale. Pilots were instructed to fly as closely as possible to each checkpoint, and to report when they believed that they were directly over each checkpoint. Pilots were briefed on the route prior to engine start at the origin airport. A sectional aeronautical chart was used to point out the route including each of the nine checkpoints.

Pilots navigated between all nine checkpoints along the flight in one of two different ways.

Eight pilots were randomly assigned to the Pilotage group. These pilots were given a San Francisco sectional aeronautical chart and were told that they would have to navigate by means of *pilotage*. Pilotage is a technique in which the pilot must find his or her way by correlating geographical features depicted on a chart with geographical features seen out the window of the airplane. These pilots were not permitted to use timers, calculators, plotters, or any other device that could facilitate navigation techniques other than pilotage (e.g., dead reckoning).

Eight pilots were randomly assigned to the GPS/Moving Map group. These pilots were given the same San Francisco aeronautical chart, but also used a panel-mounted GPS receiver that featured a moving map display. It was verified that each pilot was familiar with the basic features of the GPS and moving map prior to departure. The route consisting of all nine checkpoints was programmed into the GPS prior to takeoff.

Upon departure, pilots were asked to verbally estimate their navigational awareness in two different situations: (1) navigating using only a sectional chart; and (2) navigating using a sectional chart and a GPS receiver with a moving map display. Note that each pilot in each group rated themselves in the situation in which they were currently flying, and in the situation experienced by pilots in the other experimental group. Pilots estimated their navigational awareness using a 0-to-10 scale: 0 representing a total lack of awareness, and 10 representing perfect awareness.

All sixteen pilots flew over the nine checkpoints as instructed. All pilots were asked to announce when they believed they had reached each checkpoint. Upon each pilot report, the experimenter used a GPS receiver, hidden from the pilot's view, to note the actual distance from the checkpoint. This measure represented the pilot's navigational error.

Upon reaching the last checkpoint in the circuit, the experimenter intervened and announced a revision to the original plan for the flight. Instead of returning home, all sixteen pilots were asked to once again fly the circuit consisting of the previous six checkpoints, only this time, without any navigation resources available to them. In the case of the Pilotage group, the experimenter took away the sectional chart. In the case of the GPS/Moving Map group, the experimenter took away the sectional chart and turned off the GPS and moving map display.

After the first checkpoint, the experimenter asked each pilot to rate his or her own navigational awareness in the current situation: flying with no navigational resources other than any knowledge about the area and airspace that he or she had collected during the first time over the checkpoints.

Each pilot also was asked to provide bearing and distance estimations to what he or she believed were the two nearest airports.

The sixteen pilots flew over the loop of six checkpoints once again, reported crossing each checkpoint, while the experimenter again noted the navigational error at each checkpoint.

On the return leg, after the data were collected, all pilots were briefed on the purpose of the study and were made aware of prior human factors research pertaining to flying with automated systems.

Results

Navigation Error

The mean navigational errors for the two groups of eight pilots during the first pass through the circuit are shown in Figure 2.

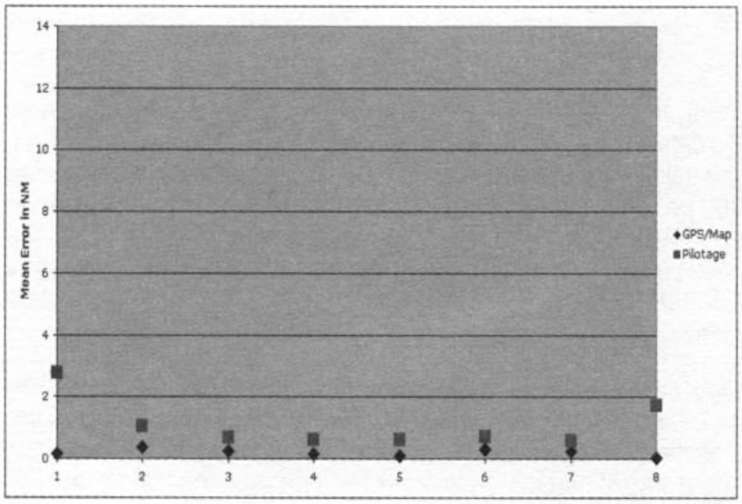

Figure 2. Navigational accuracy with all navigational resources available.

The mean navigational error and standard deviation for the Pilotage group was 1.1 NM (1.5 NM), while the mean and standard deviation for the GPS/Moving Map group was 0.2 NM (0.3 NM). Although the means for both groups fell well within the general 3 NM navigation standard for pilotage and dead reckoning cited in the Private Pilot Practical Test Standards (FAA, 2002), the GPS/Moving Map group achieved a significantly higher degree of navigation accuracy, $t = 3.74$, $p < 0.01$.

The mean navigational errors for the two groups of eight pilots during the second pass through the circuit, when pilots had no navigation resources available to them, are shown in Figure 3.

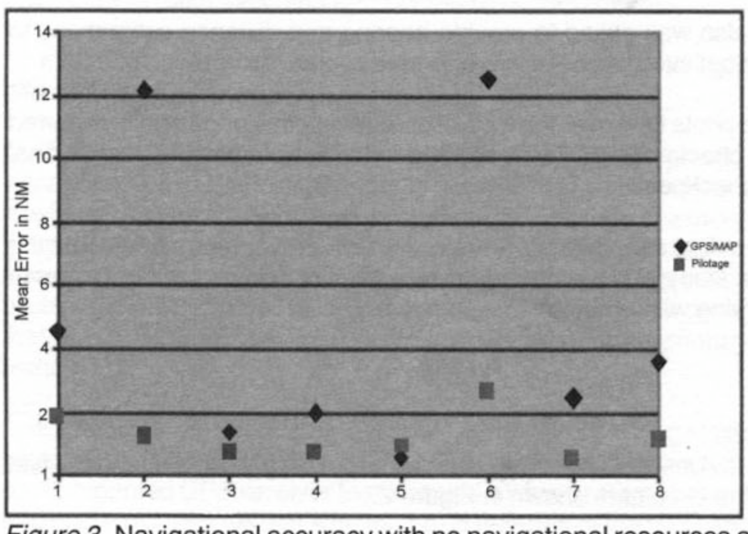

Figure 3. Navigational accuracy with no navigational resources available.

The mean navigational error and standard deviation for the Pilotage group was 1.3 NM (0.7 NM), while the mean and standard deviation for the GPS/ Moving Map group was 4.9 NM (7.9 NM). Again, there was a significant difference between the two groups, only this time the situation was reversed: the Pilotage group performed significantly more accurately ($t = 2.17$, $p < 0.05$).

Error measures and statistics aside, there was a categorical difference in performance between the two groups. All eight pilots in the Pilotage group performed within the 3 NM minimum standard suggested in the practical test standards, while only one-half of the pilots in the GPS/Moving Map group met the standard. Regardless of how one chooses to statistically consider the two large average errors shown in Figure 3, these two cases have a practical significance. These two pilots were wholly unable to find their way back to point where they started, reporting this checkpoint to be 25 NM and 41 NM away from its actual location.

Figure 4 summarizes, in a single graph, the navigational performance of both groups in both conditions.

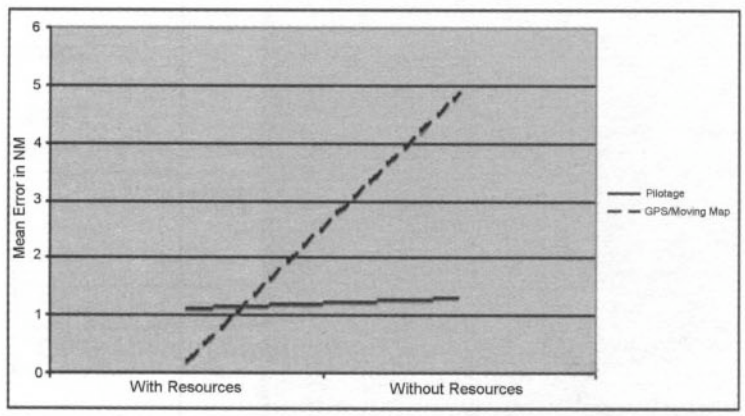

Figure 4. Navigational accuracy for both groups in both conditions.

It is also interesting to compare navigational accuracy within each of the two groups: that is, to compare pilots' performance with and without their respective navigational resources. Taking away the sectional chart had no significant effect on the performance of pilots in the Pilotage group. In fact, the variance in performance slightly decreased when the sectional chart was not available. Taking away the GPS and sectional chart from the GPS/Moving Map group had a significant effect on the mean navigational error ($t = 2.82$, $p < 0.01$).

Bearing and Distance Estimations

Fifteen of the sixteen pilots were able to identify the two nearest airports. One pilot identified the nearest airport and the third nearest airport.

The errors in bearing and distance estimations to the two closest airports for the two groups of eight pilots are shown in Figures 5 (a) and (b).

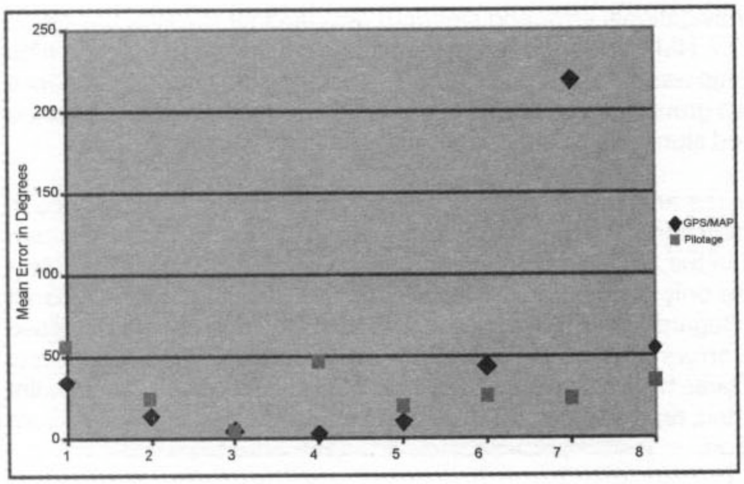

Figure 5(a). Mean error in bearing estimates for closest airports.

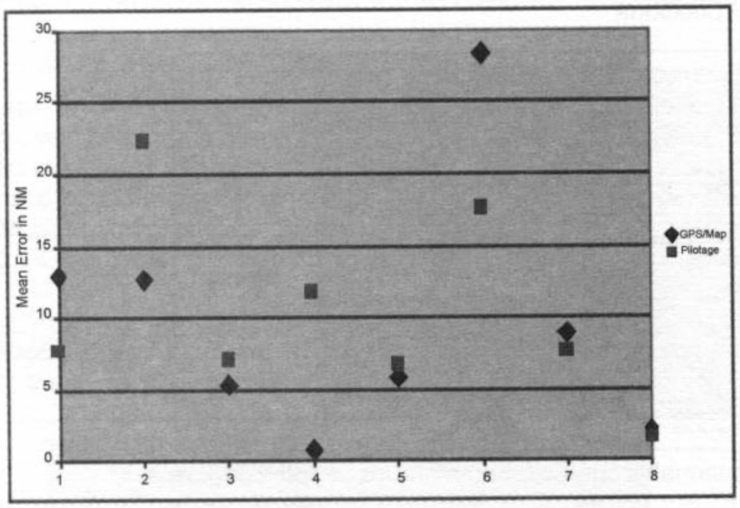

Figure 5(b). Mean error in distance estimates for closest airports.

There were no differences between the two groups. One explanation of this result is the observation that people tend to initially acquire "route-based" representations of an area. Route-based representations support basic wayfinding tasks but do not support "survey map" type tasks such as determining direction and distance between known points (Thorndyke & Hayes-Roth, 1982). This finding also casts doubt on the use of "freeze-and-probe" methods of measuring navigational awareness: techniques that focus on asking questions about navigational surroundings rather than challenging pilots with realistic navigational tasks (several studies reviewed in Uhlarik & Comerford, 2002). In this case, no difference in question-answering performance was observed between the two groups even though there was a significant difference in navigational performance between the groups.

Self-Ratings of Navigational Awareness

Every pilot was asked to rate his/her navigational awareness in three different situations:

1) Prior to traversing the circuit of checkpoints, every pilot was asked to rate his/her navigational awareness in the situation he/she was currently flying. That is, the Pilot group was asked to rate awareness when using a sectional chart, while the GPS/Moving Map group rated awareness when using a GPS, moving map, and sectional chart.
2) Prior to traversing the circuit of checkpoints, every pilot was asked to rate what his/her navigational awareness would be if he/she was flying in the other experimental condition. That is, members of the Pilotage group hypothesized what their awareness would be if they had the GPS and moving map available, while members of the GPS/Moving Map group rated themselves using only a sectional chart.
3) While traversing the circuit of checkpoints for the second time, every pilot was asked to rate awareness in his/her current situation: with no navigational resources available.

Table 1 shows the navigational awareness ratings given by pilots in both groups.

Table 1
Subjective self-estimates of navigational awareness

	Using Pilotage	Using GPS/Moving Map	Using Neither
Pilotage Group	7.625	9	8.125
GPS/Moving Map Group	6.625	9	4.875

Pilots in both groups rated awareness to be significantly greater when a GPS and moving map were being used ($t = 3.47$, $p < 0.01$). The interesting result is the significant difference between the two groups when they were confronted with the task of flying the circuit for the second time, with their navigation resources taken away. The Pilotage group rated themselves significantly higher than the GPS/Moving Map group, and these ratings matched their performance. The GPS/Moving Map group not only rated themselves significantly lower than the Pilotage group ($t = 3.38$, $p < 0.01$), but also significantly lower than themselves when flying with the GPS and map display available ($t = 4.25$, $p < 0.01$).

Performance and Total Flight Time

It is also interesting to compare pilotsí performance with their total flight time. Table 2 shows the correlation coefficients between total flight time and mean navigational error at all checkpoints.

Table 2

Correlations between total flight time and navigational error

	With Nav. Resources	Without Nav. Resources
Pilotage	-0.31	0.58
GPS/Moving Map	-0.28	-0.45

Although the pilot sample used here is small and strong conclusions are not warranted, the two larger correlation coefficients suggested the need for further investigation.

Higher flight time was associated with poorer pilotage performance when the sectional chart was taken away (r=0.58). One explanation for this effect might be that pilots rely less and less on pilotage as they acquire more flight experience.

Higher flight time was associated with better performance when the GPS and moving map were taken away. This might suggest that more experienced pilots were less likely to suffer from the out-of-the-loop phenomena when GPS and moving maps are used.

Conclusion

The results of the study provided clear answers to the two research questions. One, the pilots believed that their navigational awareness was higher when flying under VFR with GPS and moving map displays. Two, pilots' navigational awareness, using the measures described here, appeared to be significantly lower when flying with GPS and moving map displays.

With regard to the first research question, pilots' beliefs about navigational awareness warrant further investigation. It may have been that pilots responded to the question about navigational awareness without considering the possibility of an equipment failure. Furthermore, pilots may consider navigational awareness to extend beyond what the pilot is aware of in the traditional sense. That is, pilots may have considered the information stored inside the computer to be part of their awareness. This raises an important question: should we regard information stored in a computer as part of a pilot's navigational awareness? Or should this awareness be required to remain, in the traditional sense, in the pilot's head?

With regard to the second research question, the results raise the practical question of how to help pilots maintain navigational awareness when flying with advanced avionics, and how to prepare pilots for the situation in which avionics systems become inoperative during flight. Some have proposed the idea of emergency training, similar to partial panel instrument training required of all instrument rating applicants today. In the case of a vacuum system failure, pilots must rely on alternate sources of information about aircraft attitude. The results of this study suggest that this type of training would not be effective in preparing pilots for equipment outages. The data clearly showed that, unless there is another type of navigation equipment on board, there may not be another source of navigation information in the cockpit upon which to rely. Unlike vacuum systems failures, the problem with an inoperative GPS and moving map is not only a lack of information technology – it is also a lack of information. Using pilotage, our pilots had a backup navigational resource when their charts were taken away – their own knowledge of their positions, routes, and terrains. In the case of the pilots using GPS, this knowledge was not always present. We could always suggest or require that every pilot or aircraft carry an additional form of navigation equipment to help save the day (e.g., a handheld GPS). Again, there is no guarantee that this equipment will function when needed.

A promising first step toward safe use of GPS and moving maps suggested by our data is to make pilots aware of this and other cockpit automation-related human factors phenomena. These problems have been recognized and openly discussed among airline operators for twenty years (Hopkins, 1983; Manning 1984; Melvin, 1983; Oliver, 1984, cited in Wiener, 1988). The recent appearance of high-tech avionics in general aviation aircraft suggested the need to provide general aviation pilots with the same safety-related information derived from twenty years of research and operational experience. Training materials currently available for technically-advanced aircraft and equipment seldom reflect an understanding of these known breakdowns that occur when human pilots work with cockpit automation systems. Perpetuating the common belief, these documents commonly refer to the idea of "situational awareness" as something provided to the pilot by high-tech avionics. These training practices may help to magnify, not to mitigate, the unique challenges to safety presented by emerging cockpit technology.

In addition to making pilots aware of automation-related phenomena, some automation-savvy operators teach practices to help keep pilots in the loop when using automation. Cross-checking position using pilotage or radio navigation equipment is one example technique. Backing up or cross-checking calculations performed by the computer with the pilot's own mental calculations is another (Bulfer, 2004).

As a final note, it is important to note that the significantly degraded performance observed in this study occurred over a circuit of checkpoints that in no way represents the most challenging situations to be found in the national airspace system. The area used in this study was small and dense with airports and blatantly obvious geographical features (e.g. the Pacific Ocean and Sierra Mountains). Furthermore, the checkpoints were relatively close together. One only needs to imagine flying greater distances over open stretches of the Rocky Mountains or the Great Basin Desert, where the terrain can look similar in all directions for hundreds of miles. Situations like these surely raise both the challenges and the stakes in the game of finding one's way home.

References

Avidyne (2005, February). Advertisement, *AOPA Pilot*, p. 97.

Billings, C. E. (1997). *Aviation automation: The search for a human-centered approach*. Mahwah, NJ: Lawrence Erlbaum Associates.

Bulfer, B. (2004). *FMC user's guide*. Kingwood, TX: Leading Edge Libraries.

Craik, F. I. M., & Lockhart, R. S. (1972). Level of processing: A framework for memory research. *Journal of Verbal Learning and Behavior*, 11, 671-684.

Endsley, M. R. (1996). Automation and situation awareness. In Parasuraman, R., and Mouloua, M. (Eds.), *Automation and Human Performance*, (pp. 163-181).

Endsley, M. R., & Kiris, E. O. (1995). The out-of-the-loop performance problem and level of control in automation. *Human Factors, 37*(2), 381-394.

Federal Aviation Administration (2002). *Private pilot practical test standards for airplane*. FAA-S-8081-14A.

Garmin (2003). *Diamond Aircraft selects Garmin's G1000 system for new DA42 TwinStar*. Press Release: April 29, 2003.

Glenberg, A. M., Smith, S. M., & Green, C. (1977). Type I rehearsal: Maintenance and more. *Journal of Verbal Learning and Verbal Behavior, 16*, 339-352.

Hopkins, H. (1983). Over-dependence on automatics: The black box one man band. *International Journal of Air Safety 1*, 343-348.

Manning, C. K. (1984). Dangerously safe? *Air Line Pilot 53*, 22-23.

Melvin, W. W. (1983). A philosophy of automation. *Behavioral Objectives in Aviation Automation Systems Symposium*. Warrendale, PA, Society of Automotive Engineers.

Oliver, J. G. (1984). A single red light. *Air Line Pilots Association Annual Safety Symposium,* Washington, D.C.

Parasuraman, R. (1987). Human-computer monitoring. *Human Factors 29*(6), 695-706.

Savage, J. (1999, November). Situational awareness in glass cockpits. Flight Safety Foundation International Air Safety Seminar (IASS), Rio de Janeiro, Brazil.

Slamecka, N. J., & Graf, P. (1978). The generation effect: Delineation of a phenomenon. Journal of Experimental Psychology: *Human Learning and Memory, 4* (6), 592-604.

Thorndyke, P. W., & Hayes-Roth, B. (1982). Differences in spatial knowledge acquired from maps and navigation. *Cognitive Psychology 14*, 560-589.

Uhlarik, J. & Comerford, D. A. (2002). *Review of Situation Awareness Literature Relevant to Pilot Surveillance Functions.* (DOT/FAA/AM-02/3) Washington, DC: Federal Aviation Administration, U.S. Department of Transportation.

Wiener, E. L. (1988). Cockpit automation. In E. L. Wiener & D. C. Nagel, (Eds.), *Human Factors in Aviation* (pp.433-459). San Diego, CA: Academic Press.

Wiener, E. L. (1989). *Human Factors of Advanced Technology ("Glass Cockpit") Transport Aircraft.* NASA Contractor Report 177528. Moffett Field, CA. NASA Ames Research Center.